

Westerly upper air troughs and development of western disturbances over India

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ABSTRACT. The characteristics of a developing mid-tropospheric westerly trough over Indo-Pakistan area in winter season have been studied with a view to investigate its relation with western disturbances which developed and affected north and central India during that period. It was found that both were intimately connected. Light has been thrown on some other characteristic features of the western disturbances over the Indo-Pakistan region.

1. Introduction

Pisharoty and Desai (1956) defined western disturbances as "eastward moving upper air troughs in the subtropical westerlies which extend down to the lower troposphere of the north Indian latitudes in winter months". Singh (1963), Dutta and Gupta (1967) brought out in their case-studies the intimate connection of the upper westerly troughs with the intensification and movement of the western disturbances over Indo-Pakistan. It is now generally accepted that western disturbances are closely connected with the upper tropospheric westerly troughs for their development, movement and decay.

There are certain aspects of these systems, however, which are still very poorly understood. For instance, the relation between the main western disturbance and its induced ones to the south over India (earlier known as primaries and secondaries) is not yet clear. It is also the common experience of forecasters that sometimes a well marked western disturbance approaching from the west (supported by satellite cloud pictures also) suddenly weakens and passes off without causing any weather over India. Equally opposite is the case sometimes when the development over Indo-Pakistan is so sudden that forecasters are taken completely by surprise. There are also doubts regarding the frontal structure of the western disturbances and the weather activity associated with them. Thus, though studies on upper tropospheric westerly troughs and cyclonic developments in the extra-tropical latitudes have been very extensive, they are still very unsatisfactory in our region. The main reason, of course, is the lack of data over the west Asia from where western disturbances approach India.

In the following, the development of a western disturbance over Indo-Pakistan area during the period 30 December 1974 to 1 January 1975 has been studied with the help of charts of the Northern Hemisphere Analysis Centre, New Delhi, and an attempt has been made to throw light on some aspects of these systems which are still not

clear. It may be mentioned that this case was chosen for study because it was a recent one.

2. Mid-tropospheric features

Figs. 1(a) to 1(d) give the 500 mb charts from 1200 GMT of 30 December 1974 to 0000 GMT of 1 January 1975 at twelve hourly intervals, in which are included the jet streams at 300 mb.

On 30th, 1200 GMT (Fig. 1a) chart only a minor trough can be seen along 60°E extending from Aral Sea to 35° N. In the region of this trough there is deep incursion of cold air as the dipping of -30° C isotherm indicates. There are two jet streams approaching this trough from the west. The sub-tropical jet stream is in its normal position from Kuwait to Delhi and Gauhati.

By 31st, 0000 GMT (Fig. 1b) the trough has deepened considerably and lies along 67° E between 40° N and 25° N. The cold air incursion into this region has also increased with -30° C isotherm dipping to 31° N from 37° N, 12 hours earlier. A jet from the ridge upstream is approaching this trough and the subtropical jet is almost at the same location as the previous day, except near Kuwait where it has shifted north.

On the 31st, 1200 GMT (Fig. 1c) chart the trough shows further intensification and has become symmetrical with a closed circulation centred at 32° N, 71° E. The -30° C isotherm has shrunk northwards leaving a pool of cold air (temperature -30° C) in the trough. This is typically the stage of maximum development of a westerly trough (Petterssen 1956) before a "cut-off low" forms. The STJ is still passing from Isphahan to Jodhpur and further east to Dibrugarh.

At 0000 GMT of 1st (Fig. 1d) this deep upper air trough lies as a cut-off low at 31°N, 76°E. The temperature of the cold air in the centre has now risen to -25° C from -30° C indicating arrest of growth and massive subsidence (Palmen 1957). The

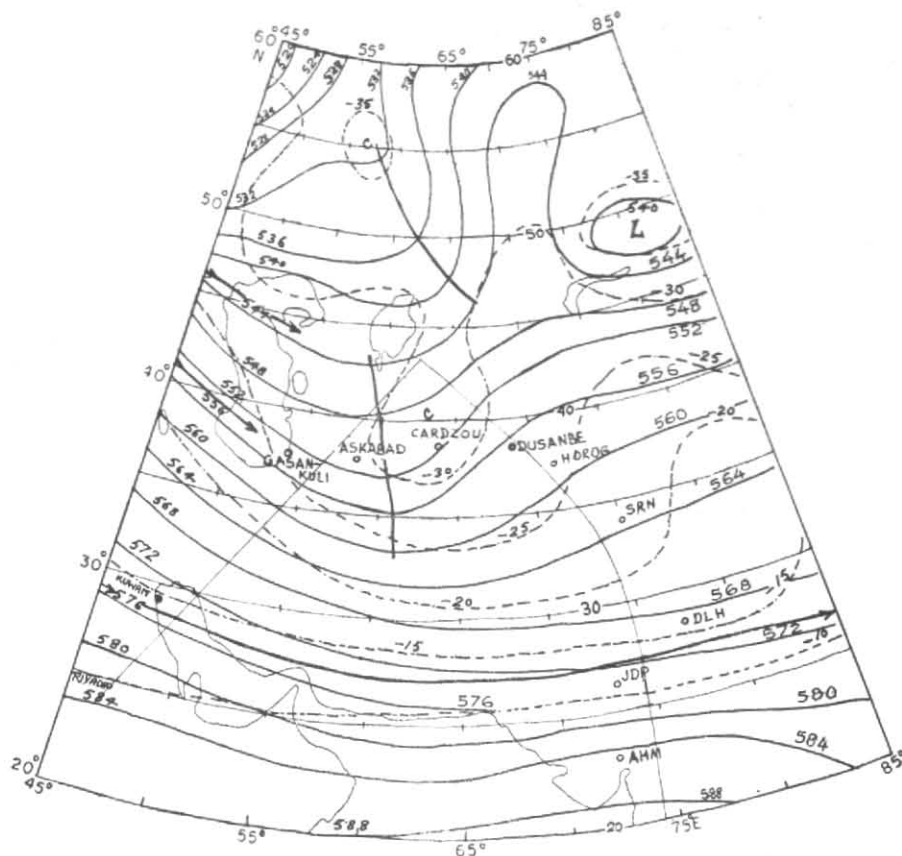


Fig. 1(a). 500 mb chart of 1200 GMT on 30 December 1974

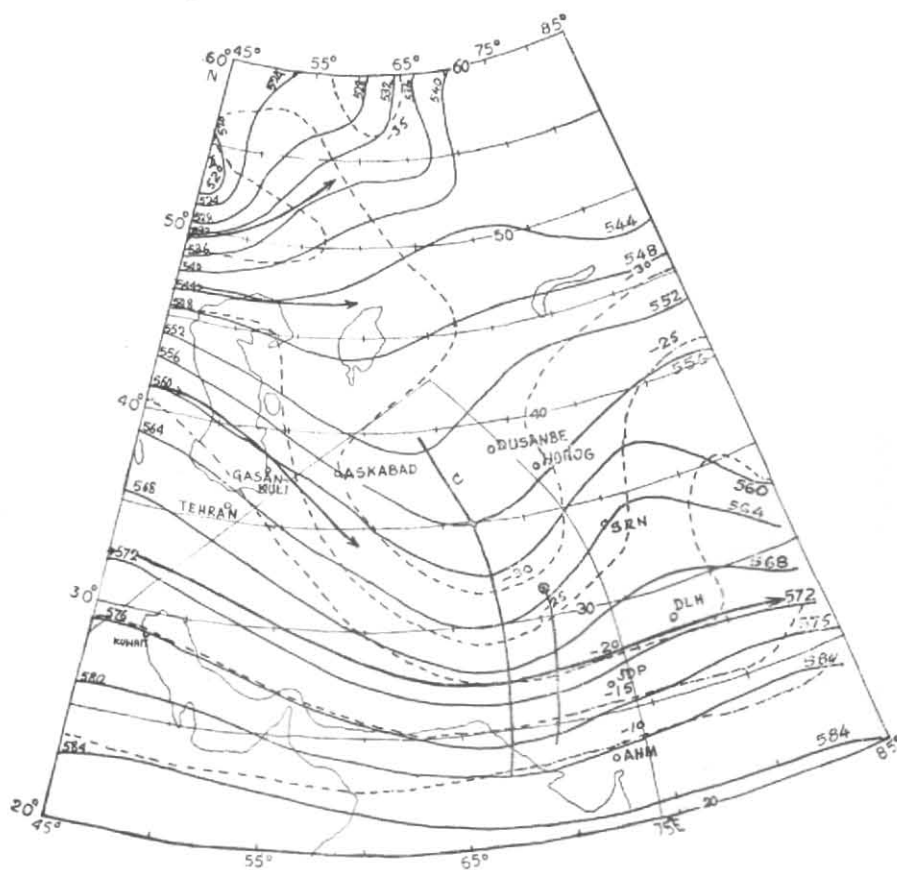


Fig. 1(b). 500 mb chart of 0000 GMT on 31 December 1974

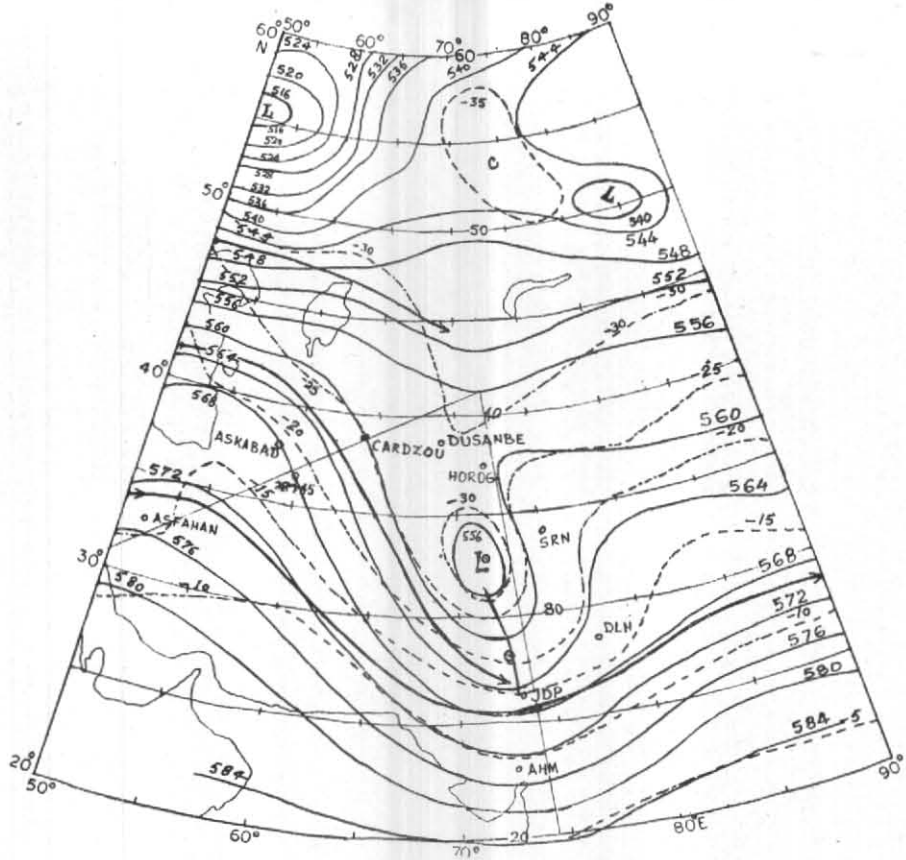


Fig. 1(c). 500 mb chart of 1200 GMT on 31 December 1974

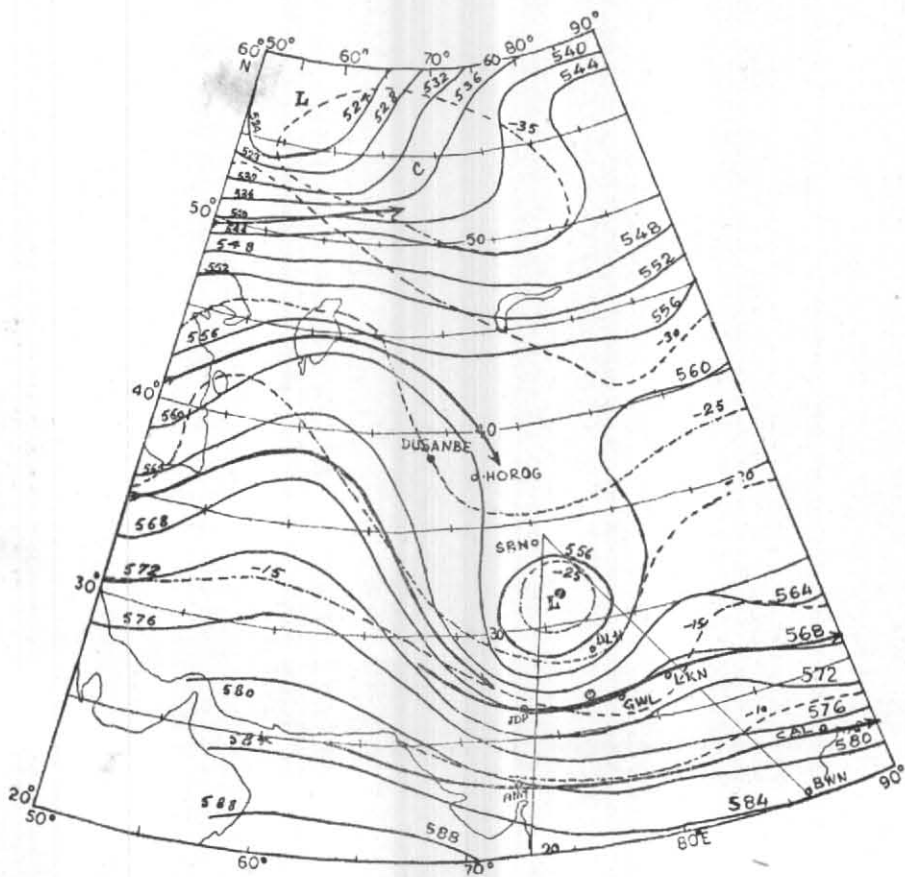


Fig. 1(d). 500 mb chart of 00 GMT on 1 January 1975

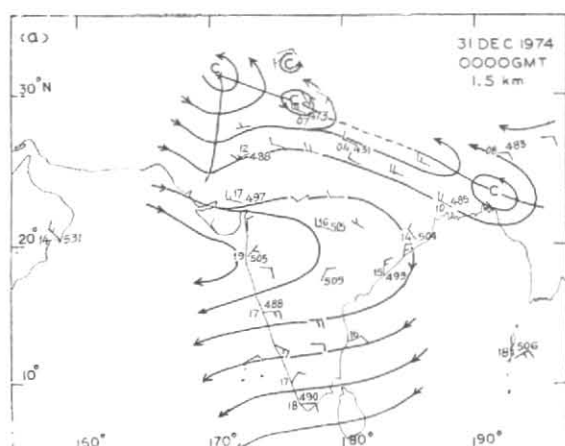


Fig. 2(a). Stream lines at 1.5 km on 31 December 1974 (00 GMT)

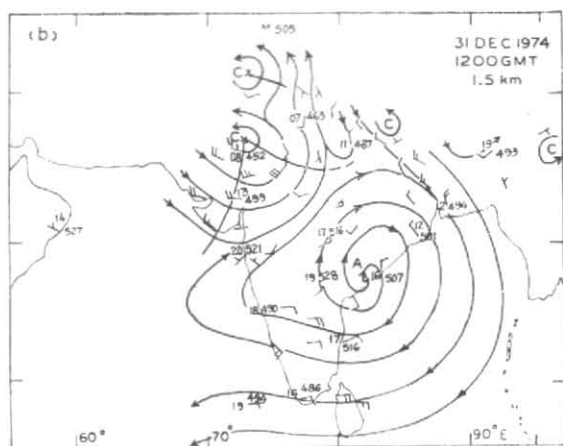


Fig. 2(b). Stream lines at 1.5 km on 31 December 1974 (12 GMT)

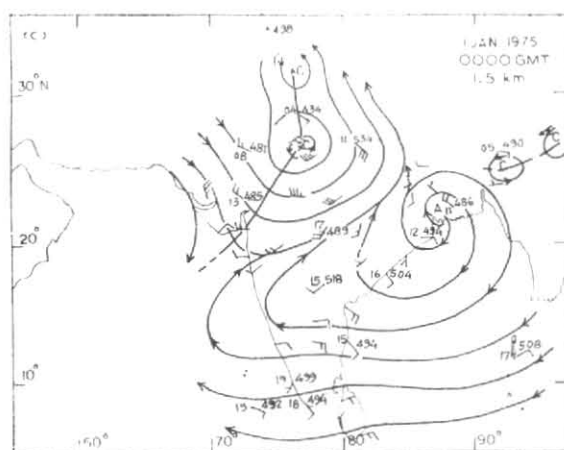


Fig. 2(c). Stream lines at 1.5 km on 1 January 1975 (00 GMT)

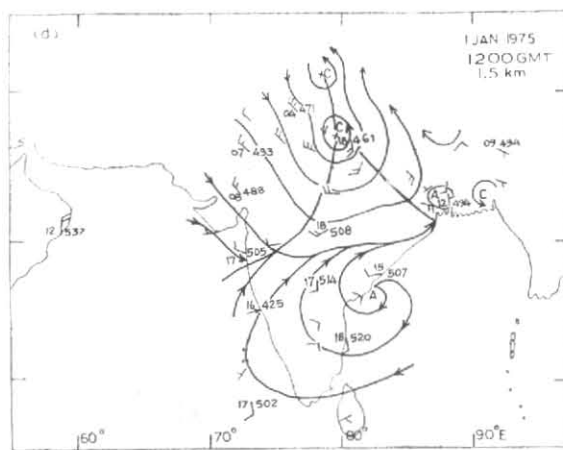


Fig. 2(d). Stream lines at 1.5 km on 1 January 1975 (12 GMT)

STJ is apparently at its usual location and is being joined by the NW'y jet approaching along the west flank of the trough.

At 1200 GMT of 1st (chart not shown) the cut-off low moving east lay at about 31°N , 79°E . It weakened further and the temperature of the cold air in the centre rose to about -21°C , showing further sinking. The NW'y jet to the west was no more seen indicating weakening of thermal gradient on the western flank of the trough. The STJ was at its usual location passing through Jodhpur, Lucknow etc.

During this period, conditions at the surface and low levels were as follows.

3. Low level features

Figs. 2(a) to 2(d) give the circulation at 1.5 km associated with the western disturbances that moved across north India during this period. It may be mentioned that during this whole period, data from

Pakistan were completely absent. Hence the lower tropospheric features in this area had to be inferred only indirectly.

On 31st morning, a feeble western disturbance could be located west of Jaisalmer on sea-level chart with the associated trough extending upto 1.5 km (Fig. 2a). To the north, a low existed over central parts of Pakistan with another trough line extending SE'wards upto Bareilly. By 1200 GMT of 31st (Fig. 2b) the sea-level low moving east deepened and was located near Phalodi with a closed circulation extending upto 2.1 km. The low to the north was located northwest of Ganganagar and was more prominent above 3 km though it was weak below. Pressure departures in the region of these lows were 4 to 7 mb below normal.

The satellite picture of the morning of 31st did not show any clouding in the regions of either of the lows. But by evening the activity was intense and rain/thundershowers occurred over central

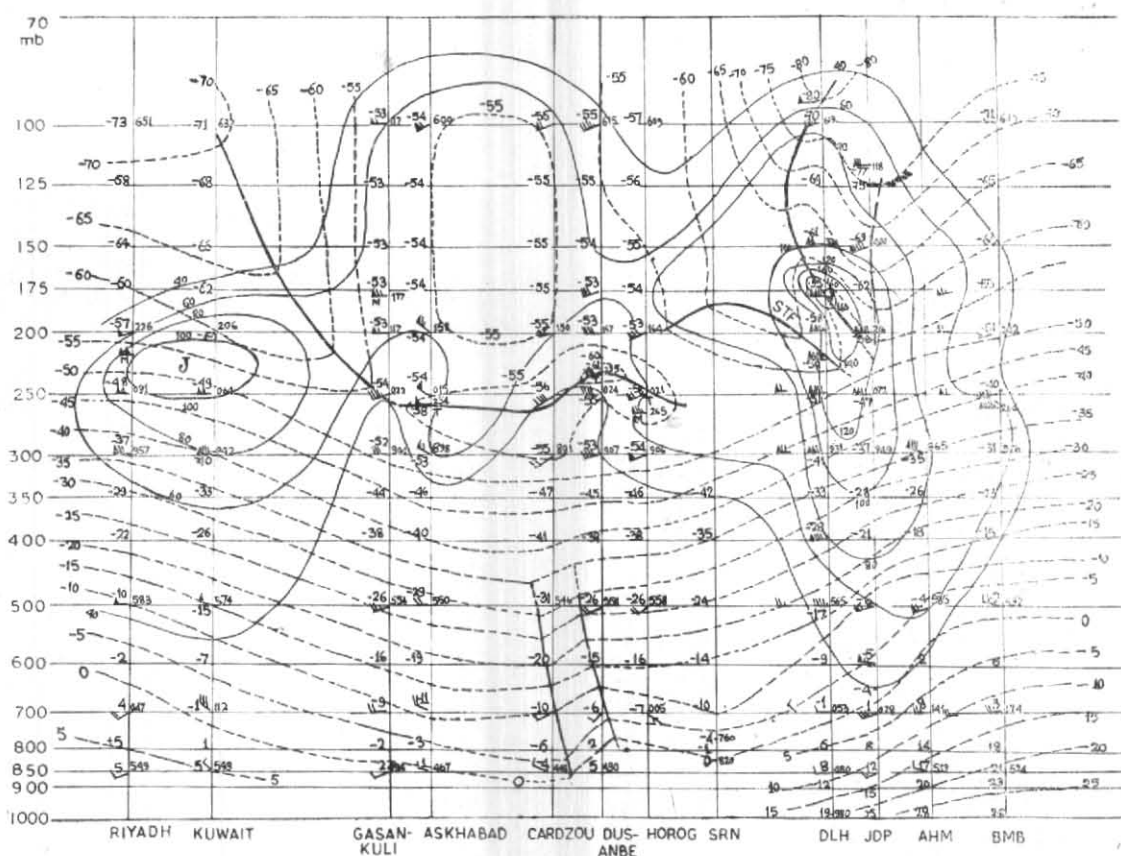


Fig. 3(a). Vertical cross-section at 1200 GMT on 30 December 1974

and west Rajasthan, Haryana, Punjab, Himachal Pradesh and northwest U.P.

By the morning of 1 January 1975, the low over Rajasthan was just to the west of Gwalior and further intensified as can be seen from the pressure departures in this region:

Gwalior	-7.3 mb	Tikamgarh	-6.9 mb
Nowgong	-6.0 mb	Guna	-6.2 mb

The associated closed circulation extended upto 2.1 km (Fig. 2c). The system to the north was near 31°N, 76°E as an upper air circulation. As usual this circulation was feeble below but well marked above 3 km.

By 1st evening (Fig. 2d) the well marked low near Gwalior weakened considerably and moved east-southeast. It further weakened by the next morning when pressure departures were only of the order of -0.5 mb or so. The circulation in the upper air was, however, still well-marked. The other circulation to its north was to the northeast of Delhi at 1200 GMT of 1st without any appreciable change in its strength. Both the circulations moved slowly eastwards.

Thus, the feeble sea level low over west Rajasthan on the 31st morning intensified into a well-marked low upto 1st morning moving east and then weakened rapidly moving east-southeastwards. The low to the north was mostly feeble in lower levels though very well marked in the upper air. Its low level features, however, could not be clearly observed for want of data.

4. Data and Analysis

As discussed earlier, the weak upper tropospheric trough developed rapidly between 1200 GMT of 30th and 1200 GMT of 31st (Figs. 1a to 1c) to become a deep system over north Pakistan. After this it became less marked and moved east slowly weakening. Apparently under its influence the low level systems behaved as discussed in the preceding section. To investigate the interaction between the upper and the lower level systems, help was taken of the vertical cross-sections across the two flanks of the upper tropospheric trough along the lines OA and OB drawn on Figs. 1(a) to 1(d).

Fig. 3(a) depicts the condition on the two flanks of the developing upper air trough over Afghanistan-Pakistan area at 1200 GMT of 30th.

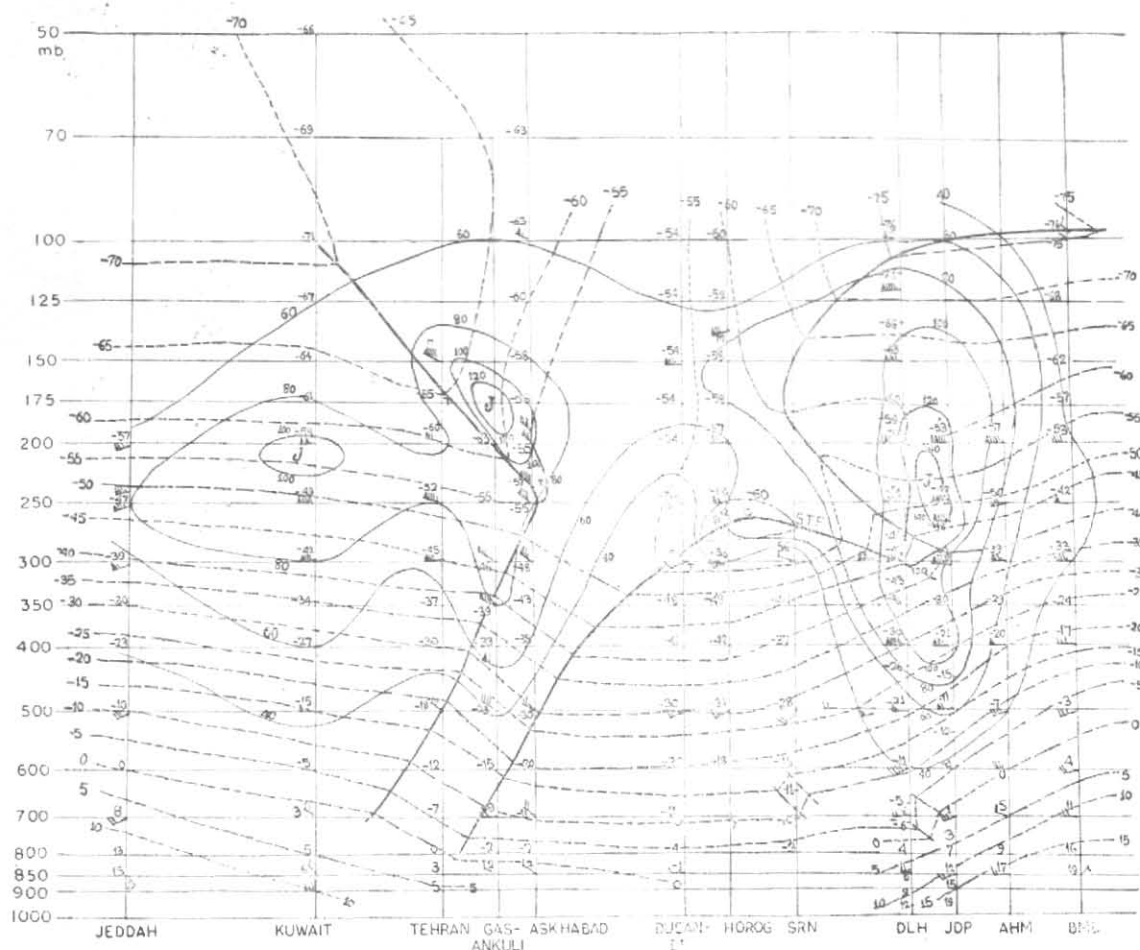


Fig. 3(b). Vertical cross-section at 0000 GMT on 31 December 1974

It can be seen in this diagram that the inflowing cold air from the north is in the centre approximately between Askhabad and Srinagar with its characteristic low polar tropopause at about 250 mb and almost isothermal stratosphere above. This cold polar air is almost barotropic but for a minor discontinuity between Cardzou (38687) and Dusanbe (38836). The warm subtropical/tropical air on the two flanks, however, seems to be highly baroclinic, particularly in the Indian region from Srinagar to Ahmedabad. On both sides, the STJ can be seen. On the west side, the core of the STJ is in Riyadh-Kuwait region above 250 mb with a speed of about 100 kt. On the east side, it is between Delhi and Jodhpur at 175 mb level with a speed of 165 knots. The stable layer close to the core of the STJ on the eastern flank (Delhi-Jodhpur) is the sub-tropical front (STF) which is normally associated with the STJ in the Indian region (Singh 1964). It is well marked but short on this day.

It is well known that in the STJ region baroclinity is normally limited to high levels. To confirm further that the deep baroclinity observed in this cross-section is not common over Indo-Pakistan during

winter season, Singh's (1971 a, b) cross-sections along 75°E from 1 to 15 February 1967 were examined. It was found that this type of baroclinity is not at all common. It is evident, therefore, that this baroclinity was the result of the incursion of warm and cold air-masses in the region of deepening upper-air trough.

In the next 12 hours (Fig. 3b) the increasing baroclinity on the west flank concentrated into a frontal surface. Though this frontal surface is not very strong, as can be expected in the west side of the trough, it is quite well marked in mid-tropospheric levels (600 to 300 mb). Associated with this is the NW'ly jet seen over Askhabad approaching from the ridge to the trough down-stream. The STJ is, however, still westerly and is over Kuwait at 200 mb. The cold air between Tehran and Srinagar is more or less barotropic. But the eastern side of the trough over Indian region is now even more baroclinic than the previous day extending from the surface to the base of the STJ (upto 250 mb). Subtropical front is still quite weak. Another cross-section from Srinagar to Bhubaneshwar including Delhi and Lucknow

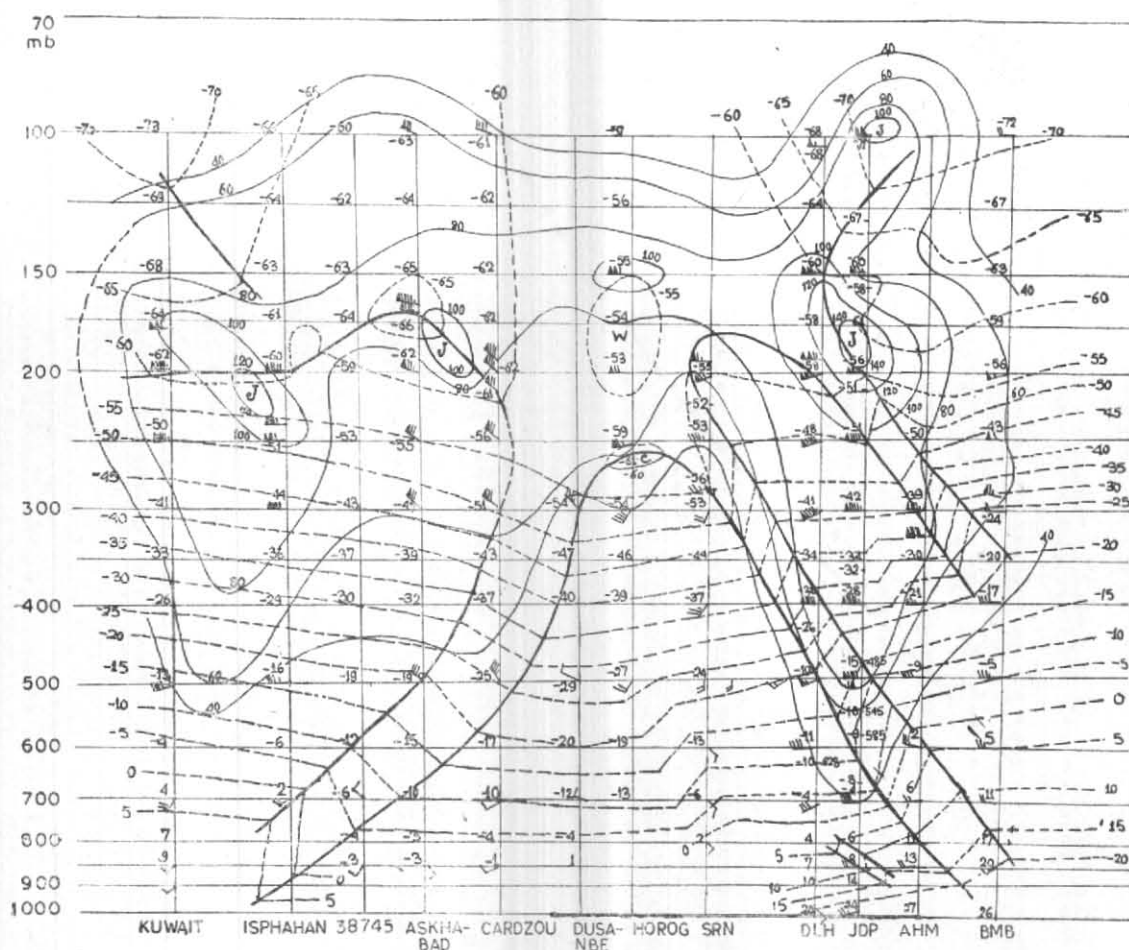


Fig. 3(c). Vertical cross-section at 12 GMT on 31 December 1974

(not shown) for this time also showed similar baroclinity. It is obvious, therefore, that with the deepening trough the baroclinity on all its sides has been increasing. On the west flank it has already concentrated into a frontal surface but on the other side it is not so as yet.

The development in the next twelve hours is interesting (Fig. 3c). The 1200 GMT cross-section of 31st shows how the frontal surface from the west has moved to the central parts of the trough extending right upto Bombay and is very well-marked. The baroclinity in this region has now disappeared, rather has concentrated into a frontal surface leaving its two sides barotropic. The frontal surface to the west has now weakened, being more tilted and well marked only in lower levels. The two jets to the west are still seen, the STJ at about 200 mb between Kuwait and Isphahan and the NW'ly jet near Askhabad, also at 200 mb.

The feeble surface low northwest of Jaisalmer (at 0000 GMT of 31st) which showed deepening at 1200 GMT of 31st near Phalodi, did so evidently under the influence of this approaching frontal surface (Palmen and Newton 1969).

In the cross-section, the low near Phalodi can be seen only as a minor discontinuity over Jodhpur

above 900 mb. Below, it is seen only as a baroclinic layer. Concentration of minor sea level troughs or fronts under the influence of approaching upper frontal surfaces has been noted by various workers (Newton 1958).

The intensification of the surface low in this situation is still more clear if we study the accompanying jet-stream. If we look at the jet-stream structure on this day over Indian area, we see that the usual STJ core is still over Jodhpur above 200 mb and the subtropical front associated with it is more active extending upto 400 mb. But the STJ structure is not normal. The level of maximum wind (LMW) extends to quite low levels with a broad band of 90 to 95 kt wind from 500 mb to the base of the STJ core (250 mb). This indicates clearly that a jet is approaching in this region. And the same becomes obvious when we see the cross-section of the 1 January 1975, 0000 GMT (Fig. 3d). Here we can see below the normal STJ-core (at 150 mb) another core of 165 kt at 350 mb. This is actually the jet which is accompanying the migrating upper level front and this is the jet whose exit region could be seen below the main STJ at Jodhpur in Fig. 3(c). Hence the intensification of the surface low at 1200 GMT of 31st in the delta region of this jet is as expected (Riehl *et al.* 1952).

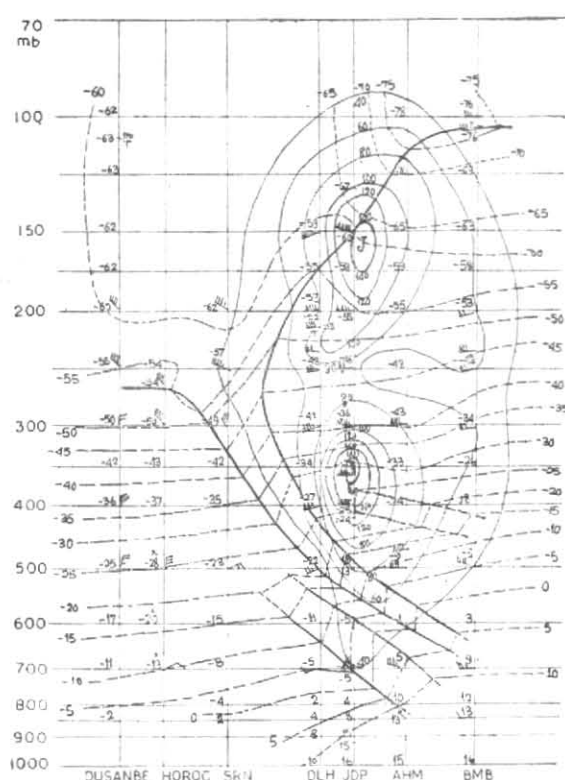


Fig. 3(d). Vertical cross-section at 00 GMT on 1 Jan 1975

In the next twelve hours, the low level system moved eastwards and became more pronounced east of Gwalior (at 0000 GMT of 1st) extending upto 600 mb (Fig. 2c). In this connection it will be interesting to examine the Figs. 3(d) and 3(e), both for 0000 GMT of 1st, one slightly to the west of the trough line covering Srinagar, Delhi, Jodhpur, Ahmedabad and Bombay and the other slightly to the east covering Srinagar, Delhi, Lucknow, Calcutta and Bhubaneshwar.

The upper level front in both Figs. 3(d) and 3(e) is much weaker than on the previous day. The core of the accompanying jet is still at Jodhpur (Fig. 3 d). Only its exit region is above Gwalior at 300 mb (Fig. 3e). It is apparent, therefore, that the surface low moving from Phalodi to Gwalior remained in the forward portion of the approaching upper level front or what is the same thing, remained in the delta region of the accompanying jet. Hence it continued to intensify as expected. In the next twelve hours, the upper front weakened considerably and so the low level system.

Thus to sum up, it may be stated that the deepening trough at 500 mb was accompanied by an upper level front which developed on its west flank and moved eastward with respect to the trough. The jet stream associated with it descended from about 200 mb on the west side to 350 mb on the trough line and intensified from 100 to 165 kt. As it approached a pre-existing feeble low at the surface near Jodhpur, the latter intensified and moved along with it, intensifying further upto 0000 GMT

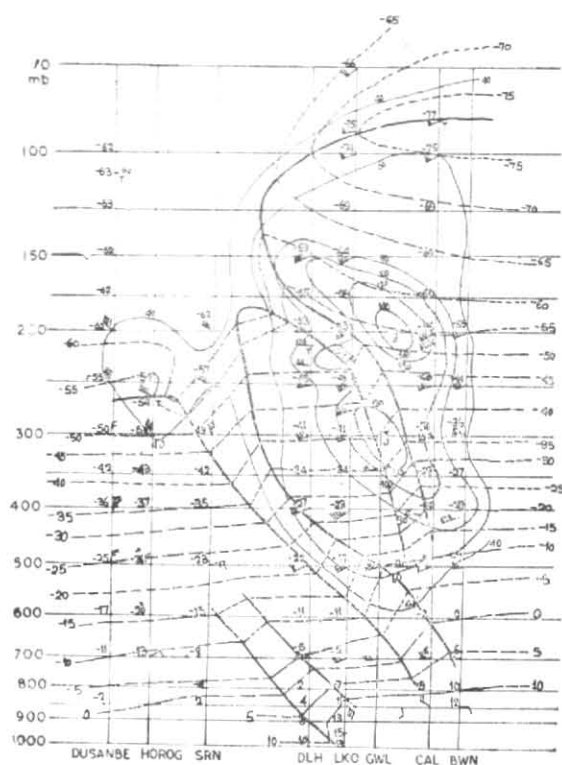


Fig. 3(e). Vertical cross-section at 00 GMT on 1 Jan 1975

of 1st after which it became weak. The upper level front too weakened gradually after 1200 GMT of 31st and was quite weak by 1200 GMT of 1st. The normal STJ and its associated subtropical front were hardly affected except that the former rose to 150 mb from 200 mb and the latter became a little more prominent during the process. The low over the Punjab finally merged with the mid-tropospheric trough at 1200 GMT of 31st (Fig. 1c). The low over Rajasthan/Madhya Pradesh developed a weak sloping frontal surface in the lower troposphere as it intensified (Figs. 3c, d, e). This frontal surface is seen separate from the mid-tropospheric front but the frontal surface associated with the low over the Punjab seems to have merged with it.

5. Discussion

It has been well established that like frontal cyclones the upper air westerly troughs too have a life cycle in that they develop and then decay taking one of the various forms discussed by Palmen and Newton (1969). It has also been shown by them that as the development of an upper air trough starts, an upper level front appears on its western side. The two then intensify together, the frontal surface moving east with respect to the trough and along it. And at the peak of the intensification of the trough the frontal surface too is the strongest and covers it entirely. In the next stage when the frontal surface moves to the eastern flank of the trough, the latter decays.

At the time when the frontal surface organises on the western flank of the trough, the temperature gradients in the central and eastern flanks are weak as can be seen in Fig. 3(b). Hence as the frontal layer moves eastwards with respect to the trough, it creates thermal diffuence of significant magnitude ahead of it. It is expected, therefore, that any pre-existing surface low lying under this diffuent region will intensify, particularly if it is at the trough line or ahead of it. It is because of this that the southeastern sector of an upper diffuent thermal trough is the most favourable region for surface cyclonic development (Sutcliffe and Forsdyke 1951).

It has also been shown by Newton (1958) that as the upper frontal layer reaches the eastern flank of the trough, it generally intensifies a surface cyclone in its northeastern sector. This cyclone finally occludes and appears as a cut-off low above. Besides, as the shifting eastward of the frontal layer heralds the decay of the upper air trough, the latter may also form a cut-off low. If this happens both the processes coincide. Sometimes the upper cut-off low itself behaves as an occluded surface cyclone. Thus in most cases, the end product of a developing upper air trough is an occluded surface cyclone.

It is apparent, therefore, that with the approach of a developing upper level trough from the west, two surface cyclonic developments are possible, one in the southeastern sector and another in the northeastern sector of the trough, the latter being mostly occluded. The appearance of western disturbances in this form is quite common over India. The northern one we call now the main and the southern one the induced. From this it is easy to understand why sometimes the main is weaker than the induced and the two are so close together (Pisharoty and Desai 1956). Also as these surface developments take place during one life-cycle of the upper air trough which is a very quick process, the intensification and weakening of the western disturbances too have to be fast. And that is what we normally observe.

This case study throws light on a few other aspects of the western disturbances which are not yet clear. Some of them will be discussed in the following.

Ramaswamy (1966) stated that though western disturbances are *prima facie* associated with fronts they have no well organised sloping surfaces associated with them. He also noted that though in the initial stages the wind and temperature discontinuities coincided in the low levels, they were soon disorganised and in any case weather pattern followed neither the wind discontinuities nor the typical system of extra-tropical cyclones. As for the structure of the western disturbance over Rajasthan/Madhya Pradesh, studied here, it is seen that there is development of a weak sloping frontal surface in the upper air in association with it. It is to be noted, however, that this western disturbance had little extension in the upper air when it intensified first (near Phalodi) at 1200 GMT of 31st

(Fig. 3c) and was still much milder (extending upto 600 mb only) on 0000 GMT of 1st when centred near Gwalior (Fig. 3e). After this, it weakened rapidly and moved away ESE'wards. Figs. 3(c) and 3(e) also show that when the western disturbance was intensifying, the upper tropospheric frontal surface was very strong and was extending upto very low levels, thus masking its mild build-up altogether. It is apparent, therefore, that wind discontinuities in the upper air at this stage will not be able to show any clear-cut relation to lower system as they are being controlled more by the upper level front and less by the western disturbance. It may also be noted that though the role of approaching diffuent upper air westerly troughs in the intensification of western disturbances has been emphasised again and again (Ramaswamy 1966), the actual mode of interaction between the two has not been brought out in our latitudes so far (as has been done in this paper). Hence the existence of two frontal surfaces in close proximity could not be visualised and without this realisation, the delineation of the sloping front of a western disturbance in the upper air with the help of wind discontinuities (as was done by Ramaswamy) will lead to a confused picture.

Coming to surface features and weather pattern it is seen that the western disturbance over Rajasthan intensified by 1200 GMT of 31st and was filled up almost completely by 1200 GMT of 1st. Thus its total life span was less than 24 hours. And this is not the unusual case but rather the normal pattern. Hence the organisation and disorganisation of a western disturbance take place so fast that to follow its frontal pattern from chart to chart is very difficult. Besides, being shallow systems they are strongly affected by the local heat/cold sources and orography which destroy their surface structure quickly. The same is the reason for the quick disorganisation of their weather activity. In the initial stages of development there is some agreement between the wind and temperature discontinuities as noted by Ramaswamy (1966) but soon the system weakens, and loses its grip on the wind system associated with it. The weather then becomes subject to local effects and shows no clear pattern. Hence, though the western disturbances are extra-tropical in origin, they are weak, shallow and shortlived in comparison to extra-tropical systems of other latitudes. There are a few other differences between the western disturbances and the extra-tropical systems over North America. Petterssen (1956) envisaged a pre-existing frontal zone at the surface for the type of development discussed here. But in our case study, it was only a trough line extending from north upto Rajasthan and a feeble low on it at the surface near Jaisalmer (Fig. 2a). Ramaswamy (1966) has noted regarding the development of western disturbances with the approach of upper westerly troughs that "Petterssen (1956) refers to pre-existing frontal zone at sea level but we would not be wrong if we assume that his hypothesis is applicable in northern Indian regions where we

have a pre-existing trough with thermal contrasts near the ground". This case study only confirms his assertion that these surface troughs behave as pre-existing surface frontal zones for the extra-tropical type development.

Newton (1958) also noted that as the lower system intensifies, it joins the upper system and both become one. In our case too, the surface low over the Punjab merged with the upper system. But the system over Rajasthan/Madhya Pradesh did not merge with it but showed a weak sloping front separate from the upper frontal surface (Figs. 3 c, d, e). It appears that the upper diffluent front moving fast over the southern surface low intensified it only weakly. And as it moved away eastwards the lower system weakened quickly before building any further.

Thus its development remained weak whereas the upper level front was very strong, and the two could not combine. In fact, Newton (1958) also does not envisage any necessity of the two merging together nor it is a dynamic requirement. It is only due to the strong development of low level system that it merges with the upper level front. In our case the movement of the upper frontal surface was too fast for the strong development of the lower system. Hence the two remained separate. Thus we can say that upper level systems move rather fast in our latitudes in comparison to those over America in winter.

6. Conclusions

(i) It has been shown in this study that deepening of a mid-tropospheric westerly trough in our region also is accompanied with the organisation of an upper frontal surface which appears first on its western side and then migrates eastward with respect to the trough and along it while it continues to intensify. The trough too intensifies in the mean time. At the peak of development of the trough, the frontal surface too is the strongest. Afterwards both seem to weaken.

(ii) The intensification of the upper westerly trough as well as the organisation and strengthening of the upper frontal surface are connected intimately with the migration southward of the cold pool of polar air from the north. This outflow is seen prominently in the upper levels, particularly at 500 mb.

(iii) As the frontal layer moves eastward with respect to the trough, it creates a thermal diffluence ahead of it. And an advancing diffluent thermal trough is the most favourable situation for a pre-existing surface low to intensify if the latter lies at the trough line or east of it below the diffluent region.

(iv) The frontal layer, as expected, is accompanied by a jet-stream whose delta region will naturally coincide with the diffluent region of the trough. And this gives the best clue to the region of surface cyclonic development.

(v) After the peak of development, the mid-tropospheric trough decays and forms a cut-off low.

(vi) Thus, on a pre-existing surface trough sometimes two western disturbances can develop, one in the southeastern sector of the mid-tropospheric trough and another in its northeastern sector. These two, when form over Indo-Pakistan region, are known as main and induced (or primary and secondary) western disturbances.

(vii) It is also noticed that the surface systems develop and decay along with the upper westerly trough with which they are associated. Hence, an upper air trough can intensify a western disturbance only in its developing stage and not in the decaying stage.

(viii) As the development and decay of an upper air trough are very fast processes, the development and decay of western disturbances too are sudden, as has been repeatedly experienced by forecasters.

(ix) It is believed that most of the induced lows over west and central India when the main western disturbances move across northern parts of Indo-Pakistan intensify in this way.

(x) The western disturbances too have sloping frontal surfaces associated with them like other extra-tropical systems. But they are weak and extend only upto 4-5 km at the most.

(xi) As western disturbances are weak, shallow and short lived, their frontal structure and weather activity get disorganised very fast.

Acknowledgement

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